GRO J1744-28: LAST GASPS OF A DYING LOW-MASS X-RAY BINARY

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ABSTRACT

We argue that the bursting, transient X-ray source GRO J1744-28 is a binary consisting of a very low-mass ($M \approx 0.2 M_{\odot}$), highly evolved giant star that is transferring mass by Roche lobe overflow onto a high-mass ($M \approx 1.8 M_{\odot}$) neutron star. We explore a picture in which the bursts are due to thermonuclear flashes in matter that has accreted onto the neutron star. We attribute the unusually hard spectra of the bursts and the high burst rate compared to normal Type I X-ray burst sources – indeed the existence of unstable nuclear burning itself – to the unusually strong surface magnetic field, $B_s \approx 1 \times 10^{13}$ G, of the neutron star.

Subject headings: Accretion — Magnetic Fields — Stars: Binary: Close — Stars: Evolution — Stars: Neutron — X-rays: Bursts

I. INTRODUCTION

Fishman et al. (1995) have reported the discovery of a rapidly bursting, transient X-ray source, GRO J1744-28, in the direction of the galactic center. The bursts last 8 to > 30 sec, (Fishman et al. 1995) and have a characteristic spectral energy $\langle E \rangle \approx 14$ keV (Briggs et al. 1996; Swank et al. 1996). The rate of bursting has declined from about 18 events per hour initially to about 1.6 events per hour (Fishman et al. 1995; Fishman et al. 1996) as the persistent emission has increased (Paciesas et al. 1996). This bursting behavior is unlike that previously seen from any transient X-ray or γ-ray source.

Recent reports that both the X-ray bursts (Kouveliotou et al. 1996) and the persistent X-ray emission (Finger et al. 1996a) from GRO J1744-28 exhibit coherent pulsations at a frequency $f = 2.14$ Hz demonstrates conclusively that both come from the same source. The lack of absorption by cold interstellar gas of the X-ray spectra of both the bursts and the persistent emission (Swank et al. 1996) suggests that the system is closer than the galactic center, while the apparent absence of an optical counterpart brighter than $m_g = 19$ or $m_r = 20.5$ (Miller et al. 1996) suggests that the system is at least 2 kpc distant. Assuming a value of 3 kpc for the distance and isotropic emission, the current persistent X-ray flux $F_p \approx 2 \times 10^{-7}$ erg cm^2 s^{-1} (Swank et al. 1996; Fishman et al. 1996) implies a persistent X-ray luminosity $L_p \approx 2 \times 10^{38}$ erg s^{-1}.

II. NATURE OF THE PULSATIONS

What can be said about the nature of the $f = 2.1$ Hz oscillations seen in the burst and persistent X-ray emission? We associate the corresponding period, $P \approx 0.5$ s, with the rotation period of the strongly magnetic neutron star. We attribute the substantial amplitude (pulsed fraction ≈ 0.5) of the pulsations in the persistent X-ray emission to funneling of the accreted matter onto the magnetic poles of the neutron star, where X-rays

are produced when the accreting matter strikes the stellar surface, as in the standard picture of accretion-powered pulsars (see., e.g., Mészáros 1992). Indeed, the X-ray spectrum of the persistent emission is similar to that of accretion-powered pulsars (Mészáros 1992), with a characteristic energy $\langle E \rangle \approx 14$ keV, and an exponential falloff above this energy (Briggs et al. 1996; Swank et al. 1996).

Further support for this picture comes from the observed frequency derivative, 8.6×10^{-12} Hz s^{-1} (Finger et al. 1996b), which corresponds to a spinup rate $\dot{P}_{\rm obs} = -5.6 \times 10^{-5}$ s yr^{-1} for the neutron star. This value is in the range expected if the persistent X-ray luminosity comes from accretion of matter onto the neutron star, and the neutron star is being spun up by the accretion torque (Ghosh & Lamb 1979), $\dot{P} = -8.3 \times 10^{-5} \mu_{30}^{2/7} (P_{0.5} L_{38}^{3/7})^2$ s yr^{-1}. Here μ_{30} is the magnetic dipole moment $\mu = B_{\rm dipole} R^3$ of the neutron star in units of 10^{30} gauss cm^3, $P_{0.5}$ is its rotation period in units of 0.5 s, and L_{38} is its accretion luminosity in units of 10^{38} erg s^{-1}. The fact that the neutron star is spinning up requires that it not be a fast rotator (Ghosh and Lamb 1979), while the lower-than-expected value of the spinup rate suggests that the rotation period of the neutron star lies near its equilibrium spin period $P_{\rm eq}$. These constraints imply $\mu_{30} \approx 1$ and thus $B_{\rm dipole} \lesssim 1 \times 10^{12}$ G.

The current persistent X-ray luminosity L_p requires a mass accretion rate $\dot{M} \approx 1 \times 10^{-8} M_\odot$ yr^{-1}, which corresponds to the Eddington accretion rate $\dot{M}_E$ for accretion over the *entire surface* of a $M \approx 1.8 M_\odot$ neutron star. However, the dipole magnetic field $B_{\rm dipole} \approx 1 \times 10^{12}$ G implied by the observed spinup rate funnels the accreting matter onto a region near the magnetic pole of the neutron star with a characteristic area $A_{\rm acc} \sim \pi (R/r_A) R^2$ corresponding to a fraction $f_{\rm acc} \sim 10^{-2}$ of the stellar surface. Consequently, the accretion rate per unit area $\dot{\sigma} \approx 10^7$ g cm$^{-2} \approx 10^2 \dot{\sigma}_E$, where $\dot{\sigma}_E$ is the mass accretion rate per unit area that yields the Eddington flux at the surface of a neutron star.

We conjecture that the ability of GRO J1744-28 to accrete at this rate is due to an unusually strong surface magnetic field $B_s \approx 1 \times 10^{13}$ G at the magnetic pole of the neutron star. Such a strong field funnels the flow onto a region near the magnetic pole of the neutron star, thereby creating a highly non-spherical geometry in which the accreting matter falls vertically onto the stellar surface while the radiation produced escapes primarily laterally out the sides of the accretion column. Equally important, a field this strong dramatically reduces the electron scattering cross section, which is the dominant opacity in the accretion column, for radiation escaping parallel and perpendicular to the magnetic field (see, e.g., Mészáros 1992). In particular, the electron scattering cross section becomes $\sigma_{e\gamma} \approx (\omega/\omega_C)^2 \sigma_T$ for extraordinary mode photons traveling at large angles to the magnetic field with energies $\hbar\omega \ll \hbar\omega_C$, the cyclotron energy. For photons with energy $\hbar\omega \approx \langle E \rangle \approx 14$ keV, $\sigma_{e\gamma} \approx (14\,\text{keV}/120\,\text{keV})^2 \sigma_T \approx 10^{-2} \sigma_T$.

Consequently, the critical luminosity, at which radiation force balances gravity, becomes $L_c \approx 5(\omega_C/\omega) L_E \approx 10^2 (B_s/10^{13}\text{ G})\, L_E$ for a plane parallel geometry (Miller 1995). For the highly non-spherical (non-plane parallel) geometry of the accretion column in GRO J1744-28, we expect an even larger value for L_c. Under these conditions, in which $L_p \approx L_c$, we expect the accretion shock to be radiation-dominated (Mészáros 1992), and the resulting emission to escape in roughly the form of a fan beam. Such a fan beam provides a natural explanation of the observed sinusoidal light curve of the persistent emission.

Similarly high accretion luminosities are seen in a number of accretion-powered pulsars having high mass companion stars, such as A0538-66, LMC X-4, and SMC X-1 (see, e.g., Stella, White, & Rosner 1986). These high accretion luminosities have never been satisfactorily explained. We conjecture that a very strong surface magnetic field $B_s \gtrsim 1 \times 10^{13}$ G may be the explanation of the high luminosities in these sources as well.

There is a substantial difference between the dipole magnetic field $B_{\rm dipole} \approx 1 \times 10^{12}$ G implied by the observed spinup rate and the surface magnetic field $B_s \approx 1 \times 10^{13}$ needed in order to make possible the accretion rate per unit area $\dot{\sigma} \approx 10^2 \dot{\sigma}_E$ that is required to explain the persistent X-ray luminosity of these sources. A similar difference is seen in, e.g., Her X-1 between the value $B_{\rm dipole} \approx 5 \times 10^{11}$ G implied by its spinup rate and the value $B_s \approx 3 \times 10^{12}$ G indicated by the energy of the cyclotron scattering feature in its X-ray spectrum (Ghosh & Lamb 1979). These differences suggest that the magnetic fields of the neutron stars in these, and perhaps other, systems are not simple dipoles.

III. EVOLUTIONARY STATUS OF THE BINARY

A timing analysis of the pulsations in the persistent X-ray emission from GRO J1744-28 has revealed a sinusoidal variation in the phase of the pulsations, implying that the X-ray source is a low-mass binary with an orbital period $P_b = 11.76$ days (Finger et al. 1996b). The companion star must have a mass $0.2 M_\odot \lesssim M_c \lesssim 1.1 M_\odot$ (see below). For an assumed neutron star mass $M_{ns} = 1.4 - 2.0 M_\odot$, the derived X-ray mass function $f(M) = 1.31 \times 10^{-4} M_\odot$ corresponds to companion star masses M_c in the range $0.2 - 1.1 M_\odot$ for inclination angles $i = 5^\circ - 25^\circ$. However, it is likely that $M_c \approx 0.2 M_\odot$, since the small values of i required for larger values of M_c are highly improbable (see Table 1).

What can be said about the evolutionary status of the binary? The relatively short rotation period of the neutron star implies that it has been accreting at a mean rate $\langle \dot{M} \rangle \approx 1 \times 10^{-8} M_\odot$ yr^{-1} for at least the spinup timescale $\tau_{\rm spinup} = -P/\dot{P} \approx 1 \times 10^4$ yrs, and most likely for far longer. The system may have gone undetected during the past twenty years or so if the mass transfer rate during this time was somewhat smaller than currently, and that consequently, the neutron star was a fast rotator and did not accrete much matter (Illarionov & Sunyaev 1975).

A mass transfer rate as high as $\dot{M}_{\rm tr} \approx 1 \times 10^{-8} M_\odot$ yr^{-1} lasting for more than 10^4 yrs is strong evidence that mass transfer in the binary is occurring via Roche lobe overflow, and consequently that the low-mass secondary fills its Roche lobe. Further evidence that the secondary fills its Roche lobe comes from the present low eccentricity $\epsilon < 0.026$ (90% CL; Finger et al. 1996b) of the binary. This implies that the low-mass secondary was once or is now comparable in size to the binary separation, in order that tidal dissipation circularize the highly eccentric binary resulting from the supernova explosion that produced the neutron star (Zahn 1977). The requirement that the secondary fill its Roche lobe and the observed binary orbital period of 11.76 days implies that the low-mass companion star is a highly evolved giant.

A binary consisting of a main sequence star and neutron star can lead to the current binary configuration of GRO J1744-28 if the mass $M_{\rm MS}$ of the main sequence star is in the range $\approx 0.8 - 1.1 M_\odot$ and the initial orbital period $P_b^0 \lesssim 10$ days. The main sequence star must have a mass $M_{\rm MS} \geq 0.8 M_\odot$ in order for it to have evolved into a giant star

within the age of the universe, and a mass $M_{\rm MS} \leq 1.1 M_\odot \approx (5/6) M_{ns}$ in order for the mass transfer process to be both conservative and stable (Joss, Rappaport, & Lewis 1987). According to this scenario, the main sequence star evolves into a lower giant-branch star, consisting of a degenerate helium-rich core and an extended hydrogen-rich envelope. When the size of the giant reaches that of its Roche lobe, mass transfer onto the neutron star commences, and continues on the nuclear burning timescale of the giant (Webbink, Rappaport, & Savonije 1983; Taam 1983). The resulting mean mass transfer rate $\langle \dot{M}_{\rm tr} \rangle \approx 5 \times 10^{-9} (P_b^0/10 \text{ days})\ M_\odot\ {\rm yr}^{-1}$ (Joss & Rappaport 1983; Paczyński 1983; Savonije 1983), is somewhat smaller, but not dissimilar to, the mass transfer rate implied by the current persistent X-ray luminosity. The initial orbital period P_b^0 must be $\lesssim 10$ days since the binary separation, and hence the binary orbital period, increases as the secondary star evolves.

The parameters of the current binary system can be calculated using the radius–core mass relationship and the luminosity–core mass relationship for lower-branch giant stars (Joss, Rappaport & Lewis 1987). We assume that, initially, the companion star had a mass $0.8 M_\odot \lesssim M_c \lesssim 1.1 M_\odot$, and a value $Z = 0.02$ for its metallicity. Table 1 shows the results for two cases: if Roche lobe overflow is just beginning, and if Roche lobe overflow is just ending. We assume values for the neutron star mass M_{ns} of $1.4 M_\odot$ and $2.0 M_\odot$ for these two cases; other values of M_{ns} are allowable, provided that, following mass transfer, the final value of M_{ns} is less than the maximum stable mass of a neutron star. Since we assume that the giant fills its Roche lobe, its properties do not depend on M_{ns}. Table 1 shows that it is highly likely that $M_c \approx M_{\rm He} = 0.20 M_\odot$, and that the mass transfer phase is just ending. It is interesting to note that the radius–core mass relationships for Population I and Population II lower-branch giants cross at $M_{\rm He} \approx 0.20 - 0.23 M_\odot$ (Joss et al. 1987), so that our predictions for the parameters of the current binary system are essentially independent of metallicity.

If our picture of GRO J1744-28 is correct, its current evolutionary status is similar to that of other LMXBs in which the companion star is a highly evolved, low-mass giant, such as Cir X-1, Cyg X-2, and the X-ray transients Cen X-4 and Aql X-1 (Lewin, van Paradijs, & Taam 1993). All of these sources have been observed to produce Type I X-ray bursts, which are thought to be due to thermonuclear flashes in matter accreted onto the neutron star, but none of them exhibit the strong, coherent pulsations in their persistent X-ray emission that are the signature of a strongly magnetic neutron star. The system GRO J1744-28 is thus unusual, in that only one other LMXB, 4U1626-67, which has an orbital period $P_b \approx 42$ min and thus an entirely different evolutionary history, exhibits coherent pulsations in its persistent X-ray emission, implying the presence of a strongly magnetic neutron star (Lewin et al. 1993).

The strong magnetic field of the neutron star in GRO J1744-28 implies that the neutron star will *not* become a millisecond pulsar (cf., e.g, Joss & Rappaport 1983), since the phase of mass transfer appears to be nearly at an end. Instead, it will eventually be observed as a normal strong-field pulsar (unless it is spun down (Illarionov & Sunyaev 1975, Ghosh & Lamb 1979) to a period $P > 3$ sec as the mass transfer from the giant companion tails off). The existence of such a strong magnetic field in an old neutron star has implications for neutron star magnetic field evolution: it may contradict a widely-

discussed picture of how millisecond pulsars are formed, in which the slowing down of the neutron star in an LMXB when mass transfer first begins leads to a loss of magnetic flux from the neutron star, reducing its dipole magnetic field from $B_{\rm dipole} \sim 10^{12}$ G to $B \sim 10^9$ G (Srinivasan et al. 1990). Relatively recent formation of the neutron star in GRO J1744-28 via accretion-induced collapse, while potentially mitigating the question of magnetic field decay, does not alter the conclusion that this system will not become a millisecond pulsar, since the phase of mass transfer appears to be nearly at an end.

IV. NATURE OF THE BURSTS

What might be the nature of the bursts produced by GRO J1744-28? The bursting behavior of the neutron star in this system is similar in some ways, but not in others, to each of the three known classes of burst sources: X-ray burst sources (Lewin et al. 1993) soft γ-ray repeaters (Hurley 1996), and γ-ray burst sources (Fishman & Meegan 1995). One possibility is that the bursts are due to instabilities in the accretion flow onto the neutron star, as is thought to be the explanation of the bursts seen in the singular source called the "Rapid Burster" (Lewin et al. 1993). Here we explore a different picture in which the bursts are due to thermonuclear flashes in matter that has accreted onto the neutron star; i.e., they are a variant of Type I X-ray bursts.

A characteristic signature of Type I X-ray bursts is $\alpha \equiv L_p/\langle L_b \rangle \approx 10{-}300$, where $\langle L_b \rangle$ is the time-averaged burst luminosity. We can re-express α in the distant-independent form $\alpha = (F_p/S_b r_b)$, where S_b is the burst fluence. In early December 1995, the burst fluence S_b was $\approx 5 \times 10^{-7}$ erg cm^{-2} in the 20-40 keV energy band, and the burst rate r_b was $\approx 5 \times 10^{-3}$ s^{-1}. Because of the difficulty in deriving F_p from Earth-occultation data in the presence of other X-ray sources in the galactic center region (particularly the bright X-ray source 1E1740.7-29, which lies only 0.8 degrees away from GRO J1744-28), the value of F_p at that time is uncertain (Paciesas et al. 1996). However, F_p was apparently $\lesssim 2 \times 10^{-8}$ erg cm^{-2} s^{-1} in the 20-40 keV energy band. This yields a value $\alpha \lesssim 10$. The unobserved flux below 20 keV could affect these numbers significantly. More recently, $F_p \approx 2 \times 10^{-7}$ erg cm^{-2} s^{-1}, $S_b \approx 3 \times 10^{-6}$ erg cm^{-2}, and $r_b \approx 4 \times 10^{-4}$ s^{-1} (Swank et al. 1996; Fishman et al. 1996), yielding $\alpha \approx 200$. Both the initial and the present α-values could differ substantially from the above estimates if the angular distributions of the burst and the persistent emission differ. Thus the α-values of the bursts from GRO J1744-28 lie in the range $\lesssim 10$ to ≈ 200, which is characteristic of Type I X-ray bursts.

The temporal evolution of α from $\lesssim 10$ to ≈ 200, correlated with an increase in L_p, that is seen in GRO J1744-28 has been observed in a number of Type I burst sources, most notably the transient X-ray sources 0748-676 and 1658-298 (Lewin et al. 1993). Within the framework of the thermonuclear flash model, such a change in the α-value of the bursts implies a transition from combined hydrogen-helium flashes to nearly pure helium flashes (accompanied by substantial steady helium burning; see Lewin et al. 1993). The observed timescale of a week or so for the transition corresponds to the timescale for approach of the neutron star envelope to thermal equilibrium. At the high mass accretion rate per unit area $\dot\sigma \approx 10^2 \dot\sigma_E$ we infer for GRO J1744-28, thermal equilibrium will be accompanied by substantial steady hydrogen burning due to electron captures deep in the envelope of the neutron star (Taam et al. 1993, 1996). If our picture of the bursts from GRO J1744-28

is correct, we predict that the more recent bursts should be shorter and have higher peak fluxes, as is typical of nearly pure helium flashes compared to combined hydrogen-helium flashes. The more recent bursts may also be accompanied by mass loss via a wind during the peak of the burst (Lewin et al. 1993).

Another signature of the thermonuclear flash model of X-ray bursts is a rough correlation between the burst rate r_b and the mass accretion rate per unit area $\dot{\sigma}$. There is substantial scatter in the correlation between r_b and L_b in GRO J1744-28. Although the burst rate is much higher (which we attribute to the much higher $\dot{\sigma}$ resulting from funneling of the accretion flow onto a small polar cap area by the strong magnetic field of the neutron star; see below), the general pattern seen in GRO J1744-28 is similar to that seen in the Type I burst source 1636-536 (Lewin et al. 1993). Indeed, erratic burst behavior of this kind is characteristic of many Type I burst sources, most notably 1735-44 (Lewin et al. 1993). Within the framework of the thermonuclear flash model of X-ray bursts, such erratic behavior finds a natural explanation in terms of low metallicity in the accreted matter (Taam et al. 1993), possibly because the mass transferred from the Population II mass-losing secondary has low metallicity or because spallation reactions in the accretion shock at the neutron star surface deplete the abundance of heavy nuclei in the accreted matter (Bildsten, Salpeter, & Wasserman 1992).

Why do thermonuclear-powered bursts occur in GRO J1744-28, but apparently not in other accretion-powered pulsars (Lewin et al. 1993)? We conjecture that the explanation lies with the unusually strong surface magnetic field, $B_s \approx 1 \times 10^{13}$ G, that we posit for the neutron star in GRO J1744-28.

Such a strong magnetic field funnels the flow of accreting matter onto a small area near the magnetic polar cap of the neutron star, as we have discussed, resulting in accretion rates per unit area $\dot{\sigma} \approx 10^7$ g cm^{-2} s^{-1}. Such a field is also strong enough to confine the accreted matter in the envelope to the region of the magnetic polar cap, since $P_{\rm gas} \lesssim (B_s^2/8\pi) \approx 4 \times 10^{24}$ erg cm^{-3}. The accreted matter thus forms a thin disk of radius $r_{\rm acc} \approx 10^5$ cm and depth $d \sim 10^2 - 10^3$ cm, at the bottom of which nuclear burning occurs.

Normally, a high $\dot{\sigma}$ leads to a very high temperature T in the neutron star envelope, due to compressional heating (Fushiki & Lamb 1987). The very high T reduces the temperature sensitivity of the nuclear reactions and stabilizes the nuclear burning. However, as we discussed earlier, a magnetic field as strong as that we posit for GRO J1744-28 dramatically reduces the electron scattering cross section, which is the dominant radiative opacity in the envelope, for radiation escaping outward from the accreted matter. The electron scattering cross section becomes $\sigma_{e\gamma} \approx (\omega/\omega_c)^2 \sigma_T \approx 10^{-2} \sigma_T$ for all photons traveling along the magnetic field and for photons in the extraordinary mode traveling at large angles to the field with energies $\hbar\omega \ll \hbar\omega_C$.

For $B_s \gtrsim 3 \times 10^{12}$ G, the peak of the photon number spectrum for a blackbody temperature $T \approx 1 \times 10^8$ K, a temperature typical of the neutron star envelope, lies at an energy $\hbar\omega \lesssim \hbar\omega_C$. Under these conditions, the enhanced radiative energy transport prevents the neutron star envelope from reaching the very high T otherwise expected for such a high $\dot{\sigma}$. It seems possible that the resulting physical conditions of density and temperature are similar to those encountered in normal Type I X-ray burst sources, and that consequently, hydrogen and helium burning are highly unstable.

In contrast, for $B_s < 3 \times 10^{12}$ G, the peak of the photon number spectrum for a blackbody temperature $T \approx 1 \times 10^8$ K lies at an energy $\hbar\omega > \hbar\omega_C$, and the surface magnetic field has little effect on the radiative opacity. Under these conditions, the temperature in the neutron star envelope reaches very high values, due to compressional heating, which stabilizes the nuclear burning. Consequently, we do not expect Type I X-ray bursts to occur in most accretion-powered pulsars.

Joss and Li (1980) found that a strong B_s, as well as a high $\dot{\sigma}$, stabilizes nuclear burning, in a study that assumed spherical symmetry and, most importantly, a very high neutron star core temperature, $T_c \approx 4 \times 10^8$ K. Under these conditions, the enhanced radiative and conductive energy transport, due to the strong magnetic field, brought the temperature in the burning shell $T_{\rm shell}$ up to $T_c \approx 4 \times 10^8$ K, which stabilized the nuclear burning. Thus, the stabilizing effect they found is a result of their particular assumption of a very high neutron star core temperature T_c. In general, and certainly in the case of a transient X-ray source like GRO J174-28, we expect the envelope and the core of the neutron star to be relatively cold (Fushiki & Lamb 1987). Then the calculations of Joss and Li (1980) do not apply, and a strong magnetic field has a strongly de-stabilizing, rather than stabilizing, effect on the nuclear burning.

Why is the X-ray spectrum of the bursts from GRO J1744-28 similar to the spectrum of the persistent X-ray emission, which has a characteristic spectral energy $\langle E \rangle \approx 14$ keV that is typical of accretion-powered pulsars? Since the surface magnetic field is sufficient to confine the accreted matter to a thin disk lying directly below the accretion column, and since the energy from the thermonuclear flash is transported primarily outward, the photon flux from the burst passes through the radiation-dominated accretion shock. In this situation, we expect the radiation from the burst to be upscattered by the accretion shock in the same way as is the radiation generated by accretion (see Meśzáros 1992 and references therein). Consequently, we expect the X-ray bursts and the persistent X-ray emission to have similar similar spectra.

Why is the burst rate r_b in GRO J1744-28 so much higher than in other Type I X-ray burst sources? If, as we suggest above, thermonuclear flashes occur in the envelope of the neutron star under conditions similar to those of normal Type I X-ray bursts, $\rho \approx 3 \times 10^5 - 3 \times 10^7$ g cm^{-3}, corresponding to column densities $\sigma \approx 10^8 - 3 \times 10^{10}$ g cm^{-2} (Lewin et al. 1993). For the very high mass accretion rate per unit area $\dot{\sigma} \approx 10^7$ g cm^{-2} s^{-1} appropriate to GRO J1744-28, this implies burst rates $r_b \sim \dot{\sigma}/\sigma \sim 3 \times 10^{-4} - 10^{-1} (\dot{\sigma}/10^7$ g cm^{-2} s^{-1}) ($\sigma/10^9 - 3 \times 10^{10}$ g cm^{-2}) s^{-1}. This is just the range of burst rates that is observed.

Lastly, we remark that one of the few Type I X-ray bursts observed from the X-ray transient Aql X-1 exhibited coherent oscillations of modest amplitude (0.1 pulsed fraction) at $f = 7.6$ Hz, which have been interpreted as due to rotation of the underlying magnetic neutron star at a period $P = 0.13$ s (Schoelkopf & Kelley 1991). Thus GRO J1744-28 may not be unique among Type I X-ray burst sources in having a significant surface magnetic field.

Tests of the thermonuclear flash model of the bursts from GRO J1744-28 include the following:

(1) Observation of a cyclotron resonant scattering line in the spectrum of GRO J1744-

28 at an energy $E_c \approx 120(B_s/10^{13}\text{G})$ keV would provide strong support for the model; conversely, observation of a cyclotron resonant scattering line at an energy significantly below this would rule out the model.

(2) Confirmation that the α-values of the bursts were ≈ 10 initially would support the thermonuclear flash model, while a much smaller upper limit on the initial value of α would pose difficulties for the model.

(3) The luminous Type I bursts produced by GRO J1744-28 are capable of disrupting the structure of the inner accretion disk, due to the radiation force and/or ablation from the outflowing wind produced by the bursts. This could lead to a reduction in the mass accretion rate $\dot{M}$, and therefore L_p, following the bursts, as observed (Swank et al. 1996). A decrease in $\dot{M}$, and therefore L_p, before the bursts would be more difficult to understand within framework of thermonuclear flash model.

V. CONCLUSION

In conclusion, if the picture that we have developed of the newly discovered bursting, transient X-ray source GRO J1744-28 is correct, the evolutionary status of the binary system is similar to that of other LMXBs with long orbital periods P_b, but the presence in it of a neutron star with a very strong magnetic field is unusual. We have explored a picture in which the bursts are due to thermonuclear flashes in the matter that has accreted onto the neutron star, and are therefore a variant of Type I X-ray bursts. We attribute the rapid burst rate and the hard spectra of the X-ray bursts from GRO J1744-28 – indeed the existence of unstable nuclear burning itself – to the unusually strong surface magnetic field of the neutron star.

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TABLE 1

Calculated Model Binary Parameters

Binary parameters	If beginning Roche lobe overflow	If ending Roche lobe overflow
$M_c(M_\odot)$	1.0	0.20
$M_{\rm ns}(M_\odot)$	1.4	2.0
$M_{\rm He}(M_\odot)$	0.23	0.20
$R_c(R_\odot)$	10.1	5.9
$L_c(L_\odot)$	29.3	12.7
$a(R_\odot)$	28.9	28.1
P_b (days)	11.76	11.76
$f(M)\,(M_\odot)$	1.31×10^{-4}	1.31×10^{-4}
i (deg)	5.2	25
Prob(i)	4×10^{-3}	0.10

a, total orbital separation; $f(M)$, mass function; Prob(i), a priori probability that the orbital inclination is $\leq i$; other parameters defined in the text.